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Evidence of a relationship between the electrical responses of the human brain and psychometric measure of intelligence is presented. These involuntary cortical responses, known as average evoked potentials are considered to be the electrical signs of information processing by the brain. The time delays of these responses from presentation of a light flash show highly significant inverse correlations with IQ scores on three common psychometric tests of intelligence in a random sample of 573 primary school pupils. Evidence is offered in support of a concept of "neural efficiency" as the biological substrate of individual differences in behavioral intelligence. Results could be useful in the development of a culture and language free measurement of intellectual potential. (Author)

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FINAL REPORT
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EVOKED POTENTIALS AND HUMAN INTELLIGENCE

October 1968

U.S. DEPARTMENT OF
HEALTH, EDUCATION, AND WELFARE

Office of Education
Bureau of Research

Final Report

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Evoked Potentials

and

Human Intelligence

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Ottawa, Canada

October 1968

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U.S. DEPARTMENT OF
HEALTH, EDUCATION, AND WELFARE

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Preface and Acknowledgements

Since the initial discovery that the human brain is a generator of electrical potentials, scientists have attempted to relate aspects of these potentials to behavioural indices of human intellectual performance. This report documents pioneering evidence that individual differences in human intelligence as measured by psychometric tests are reflected in characteristic response patterns of the brain's electrical activity.

The significant contribution of W.F. Barry, Ph.D., Head Department of Psychophysiology, University of Ottawa in securing our sample and in psychologically evaluating "anomalous" subjects is acknowledged. We further acknowledge the contribution of Mr. E. Funke of the National Research Council of Canada in developing a unique and objective computer analysis of our brain response data. The assistance of J. Wyspianski, Ph.D., Associate Professor, Faculty of Psychology, University of Ottawa in the psychometric testing of the sample is acknowledged. We also acknowledge the Ottawa Separate School Board for its co-operation in the provision of our experimental sample.

Summary

Past attempts to correlate electrophysiological variables with behavioural indices of intelligence have been inconclusive. Research to date, however, suggests that the average evoked potential (AEP) recorded from the scalp of human subjects may reflect neural correlates of higher mental activity. The late components of the evoked potential are generally agreed to be the electrical signs of information processing in the brain. The speed of this process, measured by the latency of sequential AEP components, is hypothesized as an index of neurological efficiency and possibly the intelligence of an organism. The consequent hypothesis of a relation between AEP latency and psychometric intelligence is supported by animal evidence and exploratory work with humans.

This report documents the existence of highly significant inverse correlations between the latencies of sequential visual evoked potential components and IQ scores on three commonly used psychometric tests.

The experimental sample comprised 317 male and 256 female primary school pupils randomly selected from the population of 7804 children attending grades 2,3,4,5,7 and 8 in the thirty-nine schools of the Ottawa Separate School system.

Psychometric data from each subject comprised scores on the Wechsler Intelligence Scale for Children (WISC), the Primary Mental Abilities Test (PMA) and the Otis Quick-Scoring Mental Ability Test.

All subjects were also tested physiologically for detection of their visual average evoked potential from the right parietal sensori-motor area of the brain. AEP's in response to 400 randomly delivered bright light flashes in a 625 millisecond interval following stimulation were extracted from scalp detected EEG. Computer analysis was performed to objectively identify components of the visual AEP. The latency of the first four sequential components (peaks) of each subject's visual AEP were inter-correlated with all the psychometric measures of intelligence obtained.

The major finding of this project is the observation of highly significant inverse correlations between the latency of sequential components of the visual evoked potential and IQ scores on the WISC, Otis and PMA tests of psychometric intelligence. High and low IQ subjects show evoked potential waveforms that are unique and characteristically distinct from each other. These findings provide positive evidence in support of our general hypothesis of a relationship between the electrical responses of the human brain and behavioural indices of intelligence.

A wealth of normative data on the visual average evoked potential and the three psychometric tests of intelligence used has also been obtained.

These findings and the work which should follow them could have considerable educational significance. Knowledge of the "neural efficiency" of an individual could serve as an objective, culturally independent biological assessment of mental potential useful in exploring possible racial differences in intelligence or wherever standard psychometric tests are inadequate.

Introduction

Essentially, the findings we present in this report indicate that there is a definite relationship between the electrical responses of the human brain and intelligence as defined and measured by psychometric tests.

In order to understand the nature of this work a few concepts regarding the electrical activity of the brain must be defined. The most important of these is the distinction between average evoked potentials (AEP) and the normal ongoing electrical activity of the brain referred to as the electroencephalogram (EEG). In all normal people, minute electrical currents are associated with the activity of the brain and are detectable from the intact scalp with modern electronic equipment. Apart from the voluminous clinical literature in which various forms of brain pathology are related to the EEG, remarkably little is known about the functional significance of the electrical activity of the human brain. In normal people the EEG shows a wide range of amplitude and frequency variation. The average amplitude output of various human brains can range from below 10 microvolts to over 100 microvolts. The normal frequency spectrum of this EEG activity ranges from about 6 Hz (cycles per second) to 80 Hz or more. Various frequency bands of the EEG have been assigned names, the most widely known being the "alpha rhythm", which is prominent near the visual area of the brain and is in the range of 8 - 12 Hz.

Almost from the day that it was demonstrated by Hans Berger in 1929 that it is possible to measure the electrical activity of the brain from the intact human scalp, attempts to relate variations in this activity to psychological variables was begun. There have been a number of studies dealing specifically with EEG variables and human intelligence but to date the results of these studies have been contradictory and inconclusive. Vogel and Broverman in a 1964 critical review (1) of the world literature on the question of a relationship between EEG variables and test intelligence report that such relationships are evident only in subjects who have relatively undeveloped intellectual function (feeble-minded children) or deteriorated intellectual function (brain damaged and institutionalized geriatric patients) and not in normal humans.

It would appear that only limited information can be obtained from a standard visual analysis of the ongoing EEG. The main variables of the EEG that have been studied in relation to psychological phenomena have been amplitude, frequency, phase relationships, different areas of the brain and in particular the "alpha rhythm" all with little positive payoff.

In the early 1950's, a major breakthrough in the study of human brain activity occurred with the development of techniques for detecting average evoked potentials (AEP) from the intact scalp (2). Essentially evoked potentials can be defined as non-random changes in the electrical activity of the brain in response to sensory stimulation. There is usually a train of evoked potentials or non-random electrical events occurring throughout the brain after presentation of a light flash, audible click or electric shock. But these evoked potentials are very small in amplitude and are mixed in with the ongoing EEG so that they cannot be seen with the usual methods of analysis. In order to extract these evoked potentials from the ongoing EEG an electronic averaging device is required. The principle of any averaging technique is very simple. In order to extract a signal (the evoked potentials) from noise (the ongoing EEG) some features of the signal must be non-random. In this case the latency of the evoked potential components is non-random. In other words, when a stimulus is presented to the subject his brain responds electrically always at approximately the same time after the stimulus; the ongoing EEG is mixed in with this response but is not related in time to the moment of stimulation. The averaging device adds everything, the signal and the noise, but since the noise is not temporally related to the stimulus it averages towards zero while the signal which always occurs at the same time adds up to some maximum value representing the average evoked potential after a sufficient number of identical stimuli have been presented. In this way average evoked potentials in response to a variety of discrete supra-threshold stimuli in any sense modality can be detected and studied.

With the recent widespread use of special purpose computers of average transients for the detection of average evoked potentials from the human scalp a rich fund of research information has been obtained. The effects of various stimulus variables upon AEP parameters together with inter-individual AEP differences and intra-subject AEP variations related to a variety of independent variables have all been well documented (3,4). Parameters of the AEP have been found useful for differential diagnosis in psychiatry (5), for the identification of colour blind subjects (6), and for the diagnosis of hearing disability (7).

Of even greater significance is the fact that research to date suggests that the average evoked potential recorded from the scalp of human subjects may reflect the neural correlates of higher mental activity or information processing by the central nervous system. Parameters of the AEP have been related to numerical problem solving (8), decision making (9), and the perceptual content of presented stimuli (10).

Our hypothesis of a possible relationship between the average evoked potential and psychometric intelligence derived from the consensus that the late components of the evoked potential are the electrical signs of information processing or associative activity in the brain (11,12). From this it is reasonable to postulate that a biologically efficient organism should process information more rapidly than a less efficient organism and that the delay or latency of components of the evoked potential could be a measure of the efficiency of this process. The hypothesis of a relation between AEP latency and psychometric intelligence is supported by animal evidence from normal and cretinous rats (13), AEP data from hypothyroid patients (14), and by preliminary evidence from human subjects (15,16). We now report data from a random sample of 573 primary school pupils which shows a highly significant inverse correlation between visual AEP sequential component latency and IQ scores from three commonly used psychometric tests. High and low IQ subjects show visual evoked potential waveforms that are unique and characteristically distinct from each other. For the first time, a definite relationship between the electrical responses of the human brain and intelligence as defined and measured by standard IQ tests has been established. The scope, significance and potential applications of this finding are, we feel, virtually unlimited.

Methods

The experimental sample in this project comprised 573 primary school pupils randomly selected from the population of 7804 children attending grades 2,3,4,5,7 and 8 in the 39 schools of the Ottawa Separate School system. Samples of pupils from each of the six grades were randomly drawn independently, i.e. - 97 grade two pupils were randomly selected from the population of 1709 grade two pupils in the 39 schools; 92 grade three pupils from a population of 1259; 91 grade four pupils from a population of 1254; 92 grade five pupils from a population of 1227; 105 grade seven pupils from a population of 1207; and 96 grade eight pupils from a population of 1148. The working sample of 573 pupils comprised 317 male and 256 female subjects with the age distribution shown in Figure 1 and Wechsler Intelligence Scale for Children (WISC) full scale IQ distribution shown in Figure 2.

Each subject was given three commonly used tests of psychometric intelligence: The Otis Quick-Scoring Mental Ability Test (alpha or beta); The Primary Mental Abilities Test (PMA) which provided individual ability quotients for verbal meaning, number facility, spatial relations, reasoning and/or perceptual speed as well as an overall general intelligence quotient; and the individually administered Wechsler Intelligence Scale for Children (WISC) which yielded scaled scores on eleven subtests (information, comprehension, arithmetic, similarities, vocabulary, digit span, picture completion, picture arrangement, block design, object assembly and coding) as well as verbal, performance and full scale intelligence quotients.

All subjects were tested physiologically for extraction of their visual average evoked potential. AEP's from subjects in grades 2,4 and 7 were obtained during January, February and March of 1967. AEP's from subjects in grades 3,5 and 8 were obtained during January, February and March of 1968. A random sample of 97 subjects from grades 2,4, and 7 were also retested one year later to establish the long term reliability of their visual average evoked potential.

Evoked potential records were obtained in the following manner. The EEG of each subject was recorded from bipolar scalp contact electrodes 6 cm. apart over the right parietal sensori-motor area, parallel with the midline and astride C4 in the 10 - 20 international recording system (17) with ground to the right earlobe (upward deflection in reported data indicates negativity of the anterior electrode with respect to the posterior). Electrode impedances were held below 5K ohms. The raw EEG was amplified to the required voltage in a bandwidth 3 db down at 5 and 100 Hz and recorded on multi-channel FM magnetic tape together with trigger pulses corresponding to the onset of flash stimuli. Subjects sat with eyes open in a darkened shielded room fixating a spot on a reflecting screen five feet away. A photo-stimulator lamp was located above and behind the subject outside the room so that clicks from the lamp's gas discharge tube were not audible to subjects. Bright microsecond duration photic stimuli were delivered according to a uniform stimulus interval distribution which ranged from 800 to 1800 milliseconds (msec). Average evoked potentials in response to 400 stimuli in a 625

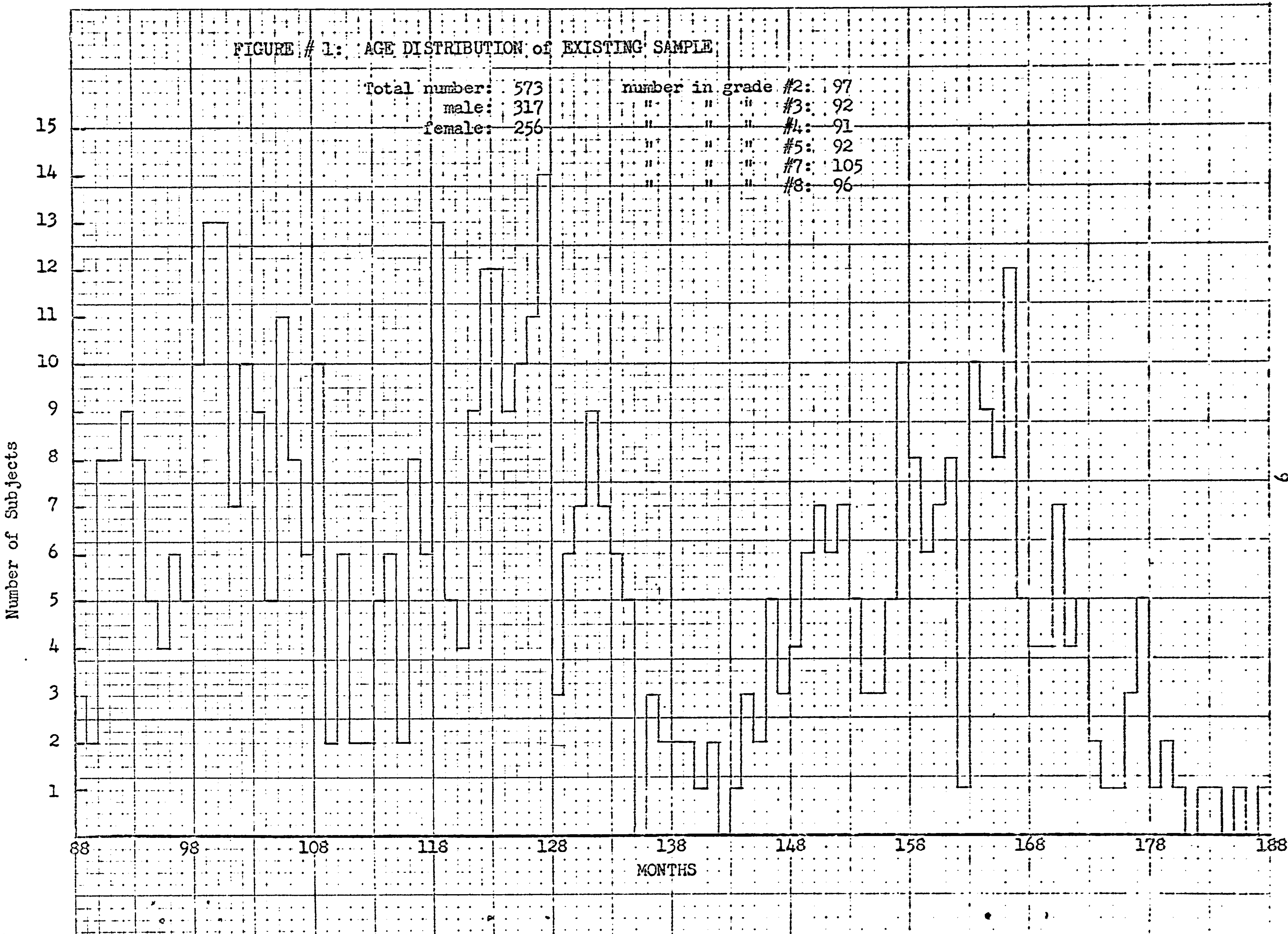


FIGURE # 1: AGE DISTRIBUTION of EXISTING SAMPLE

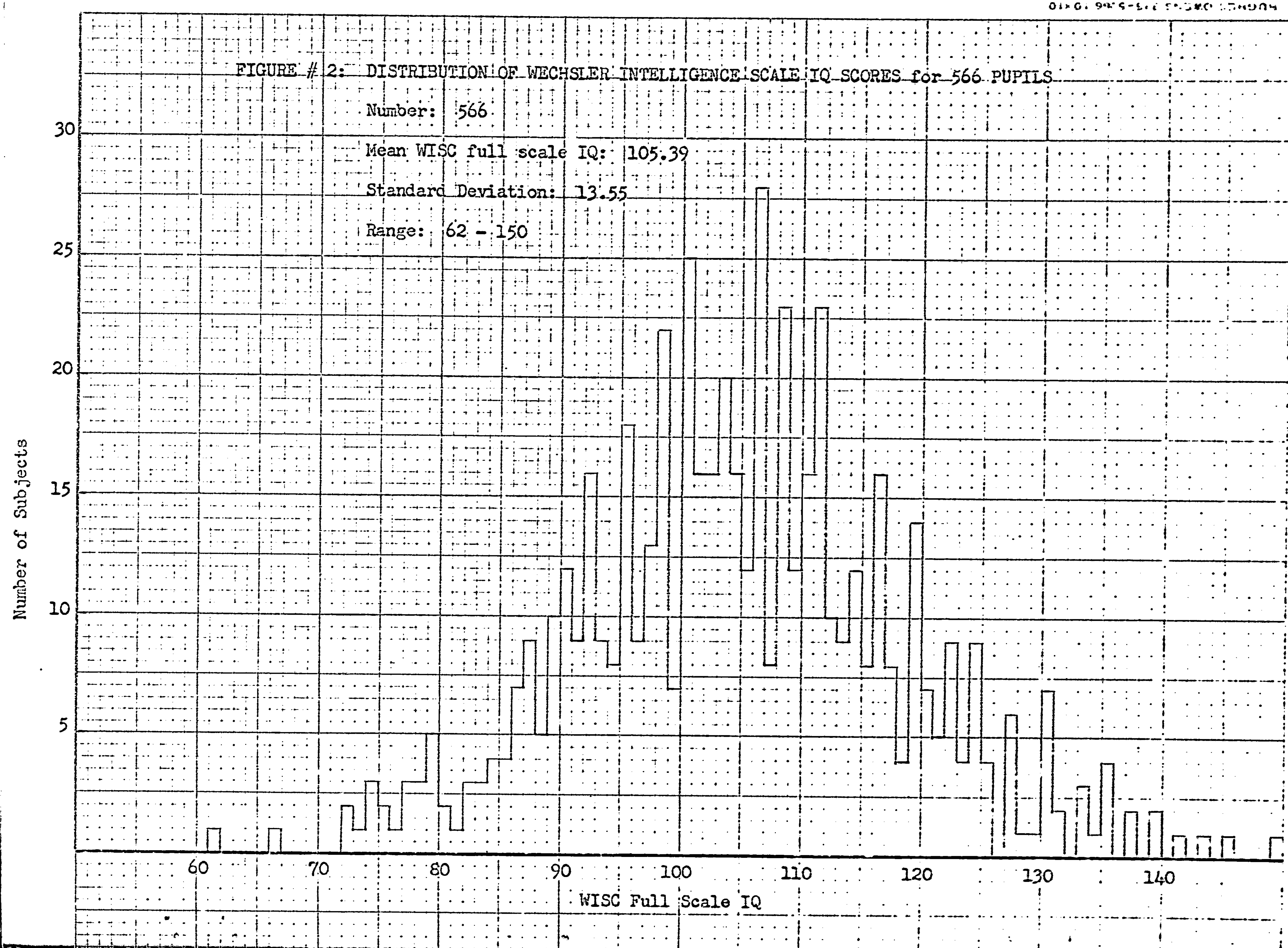


FIGURE # 2: DISTRIBUTION OF WECHSLER INTELLIGENCE SCALE IQ SCORES for 566 PUPILS
Number: 566
Mean WISC full scale IQ: 105.39
Standard Deviation: 13.55
Range: 62 - 150
Number of Subjects
30
25
20
15
10
5
60
70
80
90
100
110
120
130
140
WISC Full Scale IQ

msec interval following stimulation were extracted from the EEG filtered 6 db down at 3 and 50 Hz by two methods - conventional amplitude summation and zero-crossing analysis - using the Enhancetron ND-801 digital computer.

Using the first method, 400 evoked responses of each subject were averaged in the amplitude summation manner by the Enhancetron (1024 channels) in alternate response sets of 200 and read out by XY recorder. Short-term reliability assessments of the average evoked potential and identification of its sequential components were made by visual cross-correlation from these graphs.

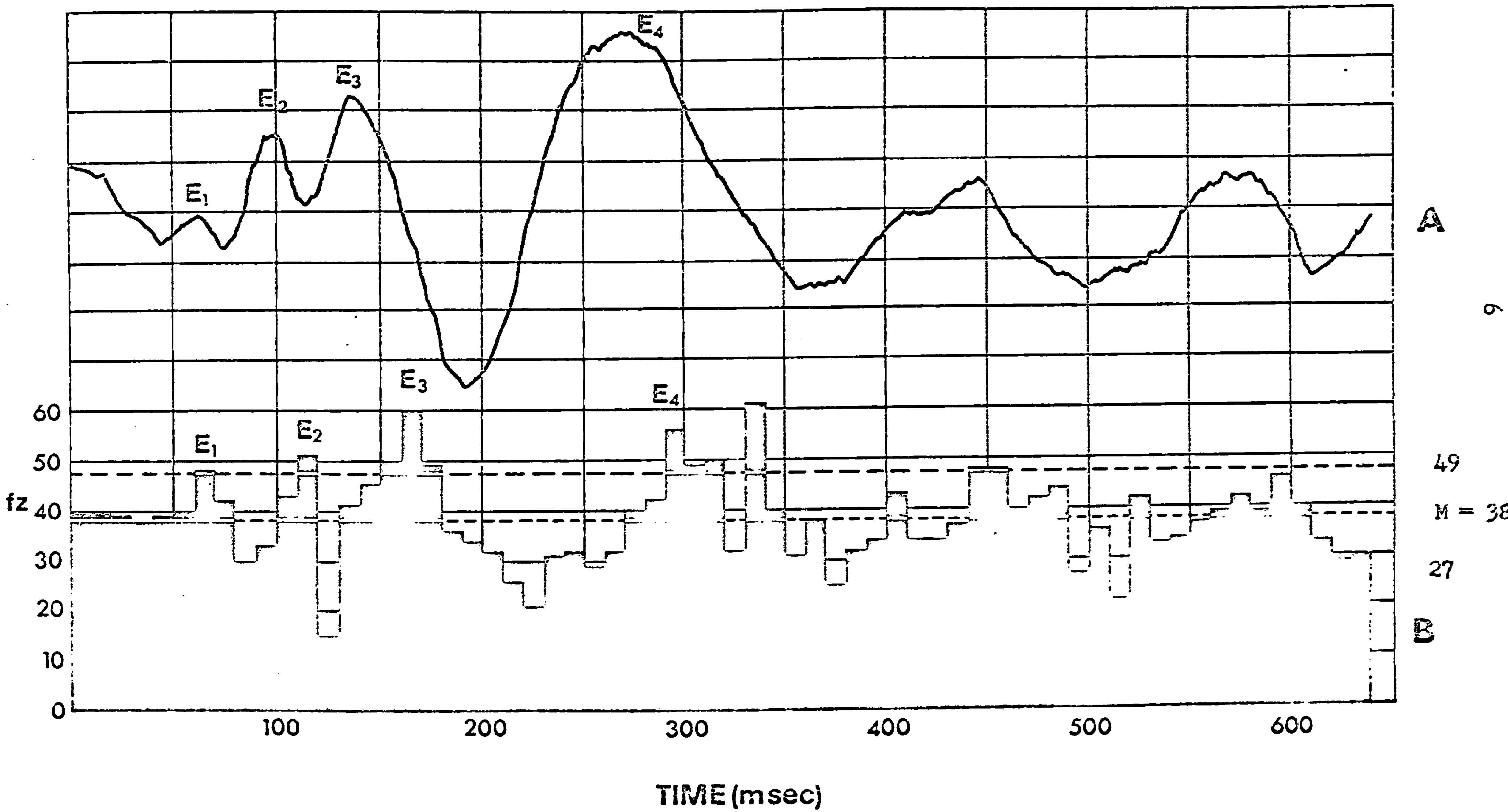
To eliminate much of the subjectivity inherent in this method of AEP component identification and to statistically determine the presence or absence of AEP components a second zero-crossing analysis technique was employed (18,19). This method facilitated identification of low amplitude, high frequency and high synchrony components which are suppressed by the conventional amplitude summation method (20). The EEG of each subject was converted to pulses corresponding to baseline crossings where the EEG waveform passed from positive to negative voltage. A distribution of zero-crossing occurrences against time following 400 stimuli (Figure 3B) was made by the Enhancetron using its multichannel scaling mode across 64 channels.

To test for the statistical presence of non-random AEP components (significantly large or small zero-crossing occurrences) the chi square test was used. It is theoretically expected and has been experimentally demonstrated (17) that under non-stimulated conditions the probability of an EEG zero-crossing occurrence is equal in any given period of time. Thus if no evoked potential components were present we would theoretically expect an equal number of zero-crossing counts in all 64 channels. The chi square test was used to identify divergence from this expectancy at any specified level of probability. Using this test the number of zero-crossing channel counts above or below the mean count needed to identify a non-random AEP component at the 1 and 5% levels of probability was determined. If the number of zero-crossing counts in any channel was greater or less than these specified values a statistically significant event (evoked potential component) was considered to be present. These events were labelled in sequence E1, E2, E3 and E4. Each event so identified corresponded in time to the zero-crossing of the average evoked potential obtained by amplitude summation of the EEG (Figure 3A). A detailed description of the precise AEP component identification decision making procedure used is given in Appendices. To gain time resolution (625 msec/1024 compared to 625 msec/64), the amplitude summated peak preceding or following each significant zero-crossing event was labelled and its latency from stimulus onset measured with an error of measurement estimated to be plus or minus 3 msec.

The latency of the first four sequential evoked potential components detected were intercorrelated with all the psychometric measures of intelligence obtained using the Pearson r correlation coefficient across the entire sample of 573 subjects. The sample was also divided into fast, average and slow responding groups on the basis of the latency of the third sequential AEP component (E3) and t tests were performed to

Figure 3: A. Amplitude summation of 400 responses to photic stimulation.

B. Histogram of zero-crossing occurrences (Fz) in 64 channels following the same 400 photic stimuli as in A. Where the height of the histogram is greater than 11 counts above or below the mean channel count (determined by chi square test at 1% probability level) an evoked potential component is statistically identified.



determine possible IQ differences between these groups. Further, the sample was divided into high, average and low IQ groups on the basis of WISC full scale IQ and t tests were performed to determine possible AEP component latency differences between these groups.

Results and Findings

This section of our report will be divided into a presentation of physiological results, psychometric results and finally findings showing a relationship between the physiological and psychometric variables.

Without exception, all 573 subjects in our experimental sample produced characteristic and measurable visual average evoked potentials from the right parietal sensori-motor area in response to 400 photic stimuli.

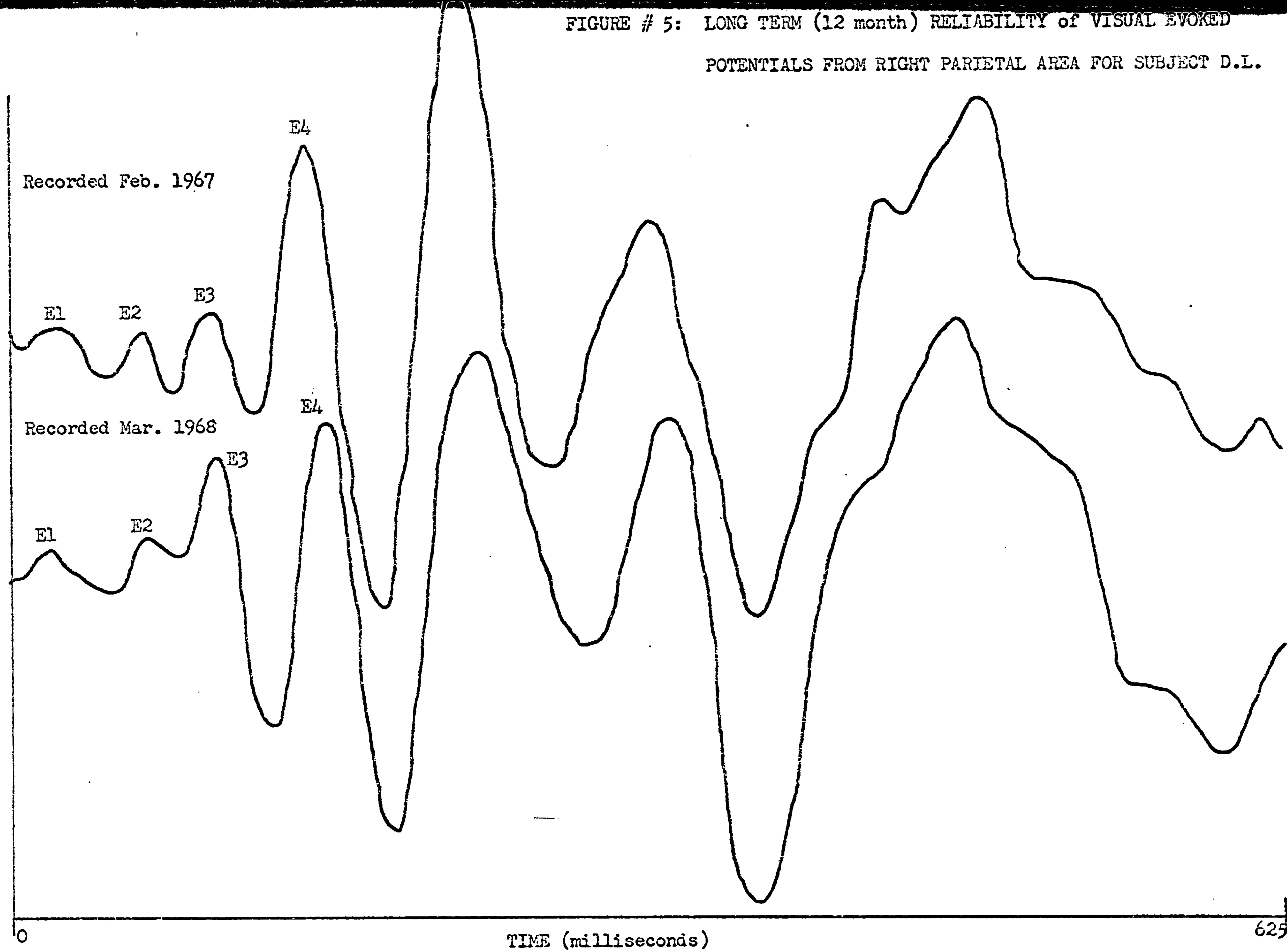
These potentials were found by visual inspection of their waveforms to have extremely high short-term reliability. That is the visual AEP in response to 200 odd numbered sequential photic stimuli was virtually identical in waveform to the AEP evoked by 200 even numbered sequential photic stimuli. The long-term reliability of the visual AEP was examined by retesting 97 subjects after a twelve month interval. Visual inspection of these first and second year waveforms indicated as might be expected that the long-term reliability of the visual AEP is not as high as the short-term reliability due principally to the variable amplitude and phase of low frequency components occurring after 250 msec from stimulus onset. The latency of sequential visual AEP components occurring in the first 250 msec after stimulation was, however, stable over the twelve month period so that the same sequential components were identified and labelled on both occasions. Specimen data is presented in Figure 4 and 5. This long-term stability of visual AEP component latencies was also demonstrated by data from one subject on 101 days across a ten month period. The following standard deviations for the latency of the first four sequential visual AEP components were obtained for this subject: E1 - 4.1 msec; E2 - 3.9 msec; E3 - 4.7 msec; E4 - 9.7 msec. Our findings regarding the short and long term reliability of average evoked potentials are supported by work in other laboratories (21,22).

No developmental changes in the latency of visual AEP components were observed. The latency of sequential visual AEP components bore no relation to age in our experimental sample which showed an age range from 88 to 188 months. Pearson r correlation coefficients between age and the latency of the first four sequential AEP components E1, E2, E3 and E4 were all insignificant across the entire sample (Table 1). Further, an analysis of variance revealed that neither age nor the interaction between age and psychometric intelligence made a significant contribution to the variability in the latency of AEP components.

No significant sex differences were noted in the latency of sequential visual AEP components. Males and females, for example, showed mean E3 latencies that differed insignificantly by only 1.26 msec.

Visual average evoked potential component latency statistics for the entire sample of 573 subjects were as follows: E1, the first AEP component showed a mean latency of 32.84 msec with a standard deviation of 13.57 and a range from 15 to 90 msec; E2, the second sequential AEP component showed a mean latency of 77.08 msec with a standard deviation

FIGURE # 5: LONG TERM (12 month) RELIABILITY of VISUAL EVOKED POTENTIALS FROM RIGHT PARIETAL AREA FOR SUBJECT D.L.



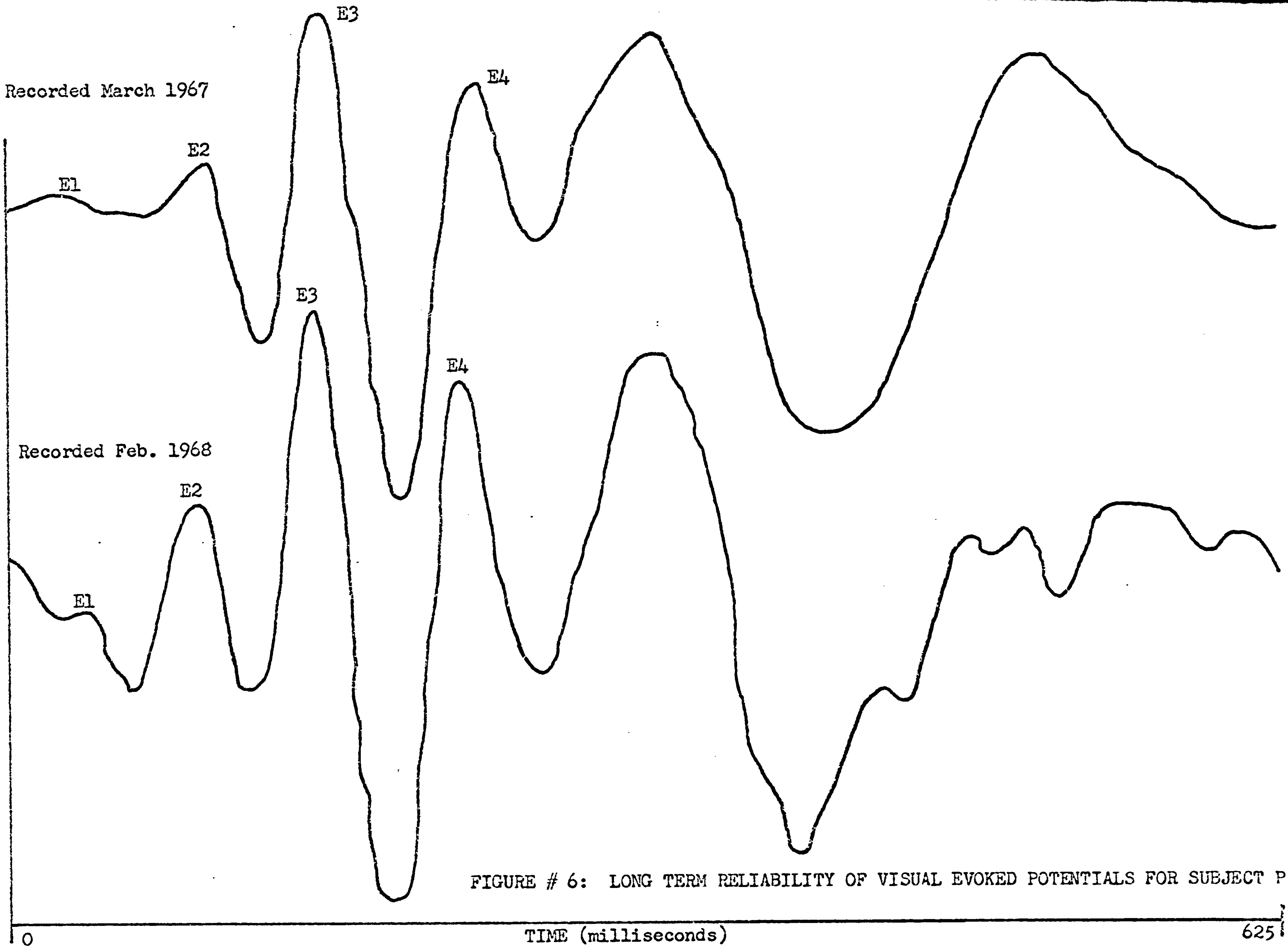


FIGURE # 6: LONG TERM RELIABILITY OF VISUAL EVOKED POTENTIALS FOR SUBJECT P.B.

Table 1: Pearson r correlation coefficients and descriptive statistics for psychometric and physiological variables

(With N of 566 Pearson r coefficients of .16 are significant at p.0001 level)

	Age	Otis	Primary Mental Abilities				WISC IQ's			AEP Latencies (msec)			
	Months	IQ	tot	verb	num	spat	full	verb	perf	E1	E2	E3	E4
Age													
Otis IQ	-.07												
PMA total IQ	.09	.75											
PMA verbal	.06	.68	.79										
PMA numerical	.08	.63	.77	.54									
PMA spatial	.03	.44	.64	.38	.38								
WISC full IQ	-.15	.61	.66	.62	.56	.44							
WISC verbal	-.11	.60	.63	.62	.59	.31	.89						
WISC performance	-.17	.48	.54	.47	.40	.47	.88	.58					
AEP: E1	-.05	-.14	-.10	-.12	-.08	-.05	-.18	-.15	-.16				
AEP: E2	-.04	-.29	-.28	-.27	-.23	-.16	-.30	-.28	-.24	.59			
AEP: E3	-.04	-.35	-.34	-.32	-.30	-.20	-.35	-.33	-.30	.43	.78		
AEP: E4	-.03	-.35	-.32	-.29	-.27	-.20	-.33	-.32	-.26	.34	.65	.83	
N	566	538	566	566	566	566	566	566	566	573	573	573	573
Mean	129.8	105.1	100.3	101.4	102.2	102.5	105.2	104.0	105.5	32.8	77.1	119.6	187.4
Std. Deviation	26.5	13.3	13.9	14.7	13.4	14.9	13.1	13.2	13.7	13.6	15.8	26.7	45.0

With N of 566 Pearson r coefficients of .16 are significant at p.0001 level of 15.82 and a range from 35 to 175 msec; E3, the third sequential component showed a mean latency of 119.58 msec with a standard deviation of 26.70 and a range from 70 to 250 msec; and E4, the fourth sequential component showed a mean latency of 187.37 msec with a standard deviation of 45.05 and a range from 90 to 430 msec. The latencies of these four sequential AEP components are all positively and significantly intercorrelated. Intercorrelations between adjacent components range from .59 to .83 and are higher than intercorrelations between non-adjacent components which range from .34 to .65 (Table 1). These sequential AEP component latency intercorrelations are, however, not so high as to preclude the possibility that each component of the visual AEP represents a distinct phase in the processing of information by the human brain. It is known that the latency and amplitude of visual AEP components can be selectively influenced by the form of the stimulus presented (10) and by the effects of a variety of pharmacological agents (23).

The distribution of the latency of the third sequential visual AEP component E3 for the entire sample of 573 subjects is given in Figure 4. It is readily apparent that the E3 latency variable does not conform to the normal distribution but appears rather to be tri-modally distributed with a clustering of values below 100 msec, a second major clustering between 100 and 140 msec and a third clustering above 140 msec. The form of this distribution may be attributed simply to the method of AEP component identification or it may in fact reflect genuine important differences in the functioning of individual human brains.

While a wealth of psychometric data has accrued from this project which may be most useful to educators and research workers specifically interested in the field, we would prefer to keep our comments on these data to a minimum concentrating rather on the physiological findings and their relationship to the psychometric variables measured.

As one would expect, psychometric intelligence (IQ) is normally distributed in our sample of 573 primary school pupils (Figure 2). The three principal measures of psychometric intelligence used are all highly intercorrelated. The Wechsler Intelligence Scale for Children full scale IQ bears a .61 correlation with the Otis IQ and a .66 correlation with the Primary Mental Abilities total IQ which in turn correlates .75 with the Otis IQ. These estimates of concurrent validity compare favourably with published findings on this subject. Various subtest intercorrelations are presented in Tables 1 and 2 without comment.

The small but significant inverse correlation between age and WISC IQ can be accounted for by our procedure of sampling by grade and the selective academic failure of older low IQ subjects at a given grade level.

The major and most significant finding of this project is the observation of a relationship between the electrical activity of the human brain and intelligence as measured by standard IQ tests. More particularly we have observed highly significant inverse correlations between the latency of sequential components of the visual average evoked potential and IQ scores on the Wechsler Intelligence Scale for

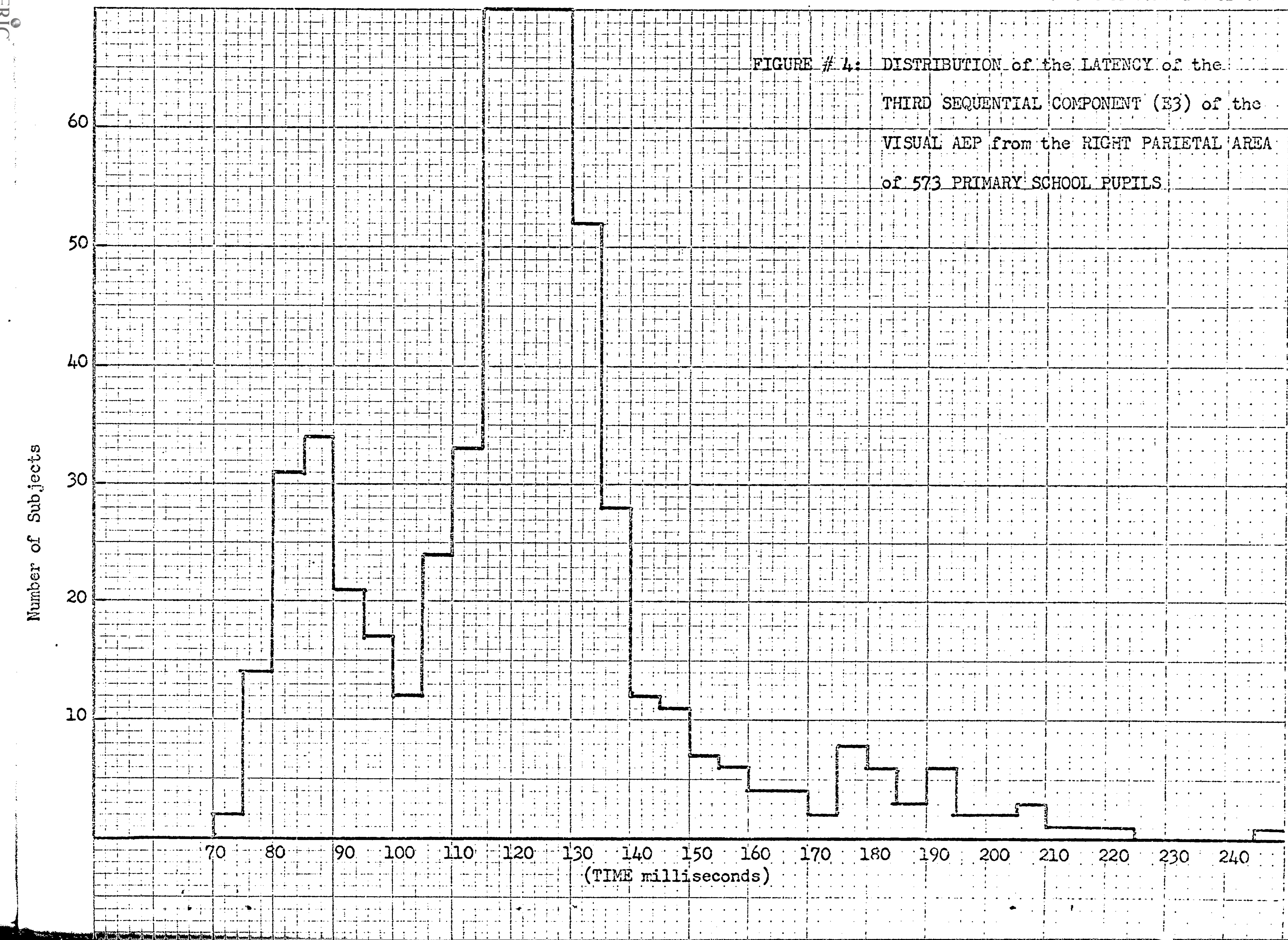


FIGURE # 4: DISTRIBUTION of the LATENCY of the THIRD SEQUENTIAL COMPONENT (E3) of the VISUAL AEP from the RIGHT PARIETAL AREA of 573 PRIMARY SCHOOL PUPILS
Number of Subjects
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
(TIME milliseconds)

Table 2: Pearson r correlation coefficients relating WISC subtests to other psychometric and physiological variables for sample of 566 primary school pupils

	Wechsler Intelligence Scale for Children (IQ's and subtest scaled scores)													
	Full IQ	Verb	Perf	Inf	Comp	Arith	Simil	Vocab	Dgt sp	P.Comp	P.Arrg	Bl dsg	Ob asm	Cod
Age	-.15	-.11	-.17	-.10	-.03	-.17	-.06	-.07	-.09	-.00	-.12	-.26	-.15	-.02
Otis IQ	.61	.60	.48	.54	.24	.48	.48	.52	.40	.27	.35	.44	.26	.32
PMA total IQ	.66	.63	.54	.54	.29	.48	.50	.56	.38	.28	.38	.43	.33	.41
PMA verbal	.62	.63	.47	.54	.34	.37	.47	.61	.30	.29	.38	.31	.25	.35
PMA numerical	.56	.59	.40	.54	.26	.54	.47	.45	.35	.18	.29	.32	.23	.32
PMA spatial	.44	.31	.47	.27	.10	.24	.29	.28	.21	.27	.27	.46	.36	.21
WISC full IQ		.89	.88	.71	.61	.62	.66	.73	.44	.55	.65	.68	.59	.46
WISC verbal	.89		.58	.78	.71	.67	.73	.81	.53	.35	.45	.46	.34	.33
WISC performance	.88	.58		.48	.37	.42	.44	.48	.25	.65	.71	.75	.72	.50
information	.71	.78	.48		.41	.43	.51	.59	.32	.32	.34	.39	.28	.27
comprehension	.61	.71	.37	.41		.32	.39	.54	.13	.26	.34	.25	.19	.19
arithmetic	.62	.67	.42	.43	.32		.40	.40	.40	.13	.32	.39	.28	.28
similarities	.66	.73	.44	.51	.39	.40		.54	.22	.29	.30	.36	.24	.25
vocabulary	.73	.81	.48	.59	.54	.40	.54		.21	.35	.40	.37	.28	.22
digit span	.44	.53	.25	.32	.13	.40	.22	.21		.03	.21	.22	.17	.20
picture completion	.55	.35	.65	.32	.26	.13	.29	.35	.03		.32	.36	.32	.12
picture arrangement	.65	.45	.71	.34	.34	.32	.30	.40	.21	.32		.43	.42	.20
block design	.68	.46	.75	.39	.25	.39	.36	.37	.22	.36	.43		.53	.22
object assembly	.59	.34	.72	.28	.19	.28	.24	.28	.17	.32	.42	.53		.17
coding	.46	.33	.50	.27	.19	.28	.25	.22	.20	.12	.20	.22	.17	
AEP: E1	-.18	-.15	-.16	-.11	-.12	-.04	-.14	-.17	-.04	-.09	-.10	-.14	-.10	-.10
AEP: E2	-.30	-.28	-.24	-.23	-.20	-.16	-.22	-.29	-.11	-.12	-.20	-.20	-.14	-.17
AEP: E3	-.35	-.33	-.30	-.26	-.22	-.22	-.23	-.34	-.18	-.15	-.27	-.26	-.16	-.17
AEP: E4	-.33	-.32	-.26	-.25	-.22	-.24	-.22	-.33	-.17	-.14	-.24	-.24	-.16	-.11

With N of 566 Pearson r coefficients of .16 are significant at p.0001 level

Children (WISC), the Otis Test of Mental Ability and the Primary Mental Abilities test (PMA) (Table 1 and 2). These correlations range in magnitude from .10 (between E1 and PMA total IQ) to .35 (between E3 and WISC full scale IQ). It would appear that the electrophysiological measures are related to some common factor tapped by all the intercorrelated psychometric tests. The correlations of every psychometric test and its subtests are higher with the late components (E3 and E4) of the AEP than with the early components (E1 and E2), with E3 bearing the highest correlations of all four components. In view of the large sample used to generate these correlations and the large number of individual estimates of psychometric intelligence taken, it is highly improbable that such a trend could be due to chance. Further, this observation accords well with the generally accepted position that the late components of the AEP are reflections of higher mental activity.

While the AEP component latency - IQ intercorrelations are not large they are nevertheless highly significant statistically. When investigating a theoretical problem and/or attempting to relate variables in the psychological domain to variables in the physiological domain, it can be argued that even very small correlations, if statistically significant, could be indicative of a fundamental law. We feel that such is the case with the present findings. It is our contention that the latency of sequential components of the visual AEP is an index of neurological efficiency which manifests itself differentially in standardized estimates of intelligent behaviour (IQ scores).

The relative magnitude of the latency - IQ intercorrelations can perhaps be explained by the non-normal distribution of AEP latencies and the somewhat questionable reliability and validity of IQ scores at the individual subject level (52 subjects showed IQ differences between the WISC and PMA tests which exceeded 20 points). We have consequently further tested the relationship between AEP latency and IQ with t tests across groups of subjects divided on the basis of E3 latency and WISC IQ (Tables 3 and 4). There can be no doubt that fast E3 latency subjects show higher WISC IQ's than average or slow latency subjects. Alternately, high WISC IQ subjects show shorter E3 latencies than average or low IQ subjects.

Specimen AEP waveforms for ten high and ten low IQ subjects are shown in Figure 8. Even without latency measurements it is evident that these two sets of waveforms are different in configuration. The high IQ subjects show high frequency early components in the first 100 msec which are not present in the AEP's of the low IQ subjects. We are presently working on the development of a computer pattern recognition technique which should obviate the measurement of AEP component latency and in turn identify high, average and low IQ subjects simply by the configuration of their AEP waveforms.

It is known that a large number of variables affect the waveform of the visual AEP particularly in the amplitude domain (24). The inter-individual AEP component latency differences noted in our sample, however, are much greater than any latency changes attributable to variables such as attention, arousal level, pupil diameter, etc. It was impossible to

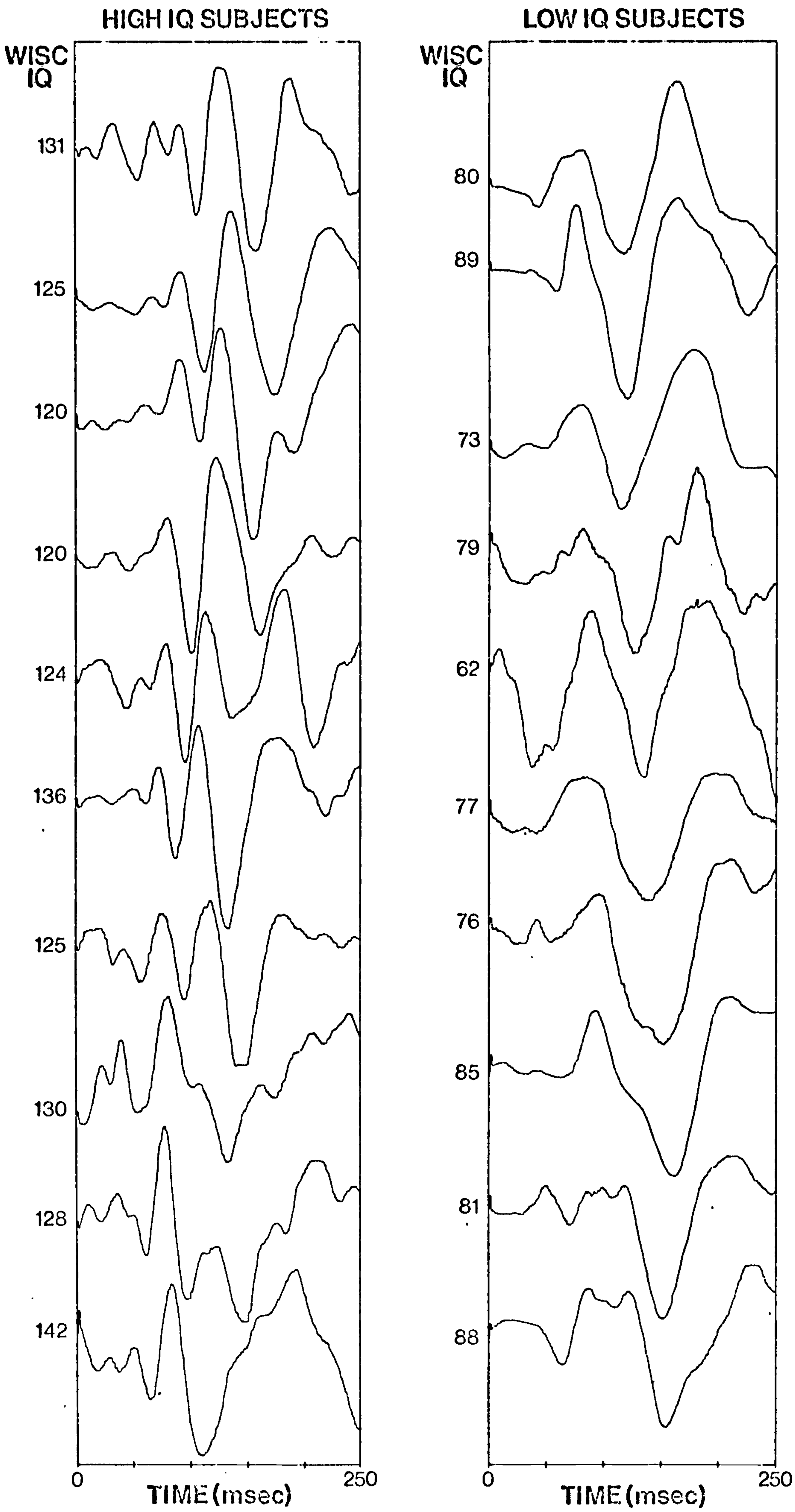
Table 3: Mean WISC Full Scale IQ Differences for Fast, Average and Slow Visual AEP E3 Latency Subjects

Group	Number	Mean	Std Dev	Mean Difference	t	df	Significance
Fast: 95 msec or less	111	111.78	14.57				
				6.31	4.58	485	p .00001
Average: 96-145 msec	376	105.47	12.23				
				11.12	6.70	434	p .00001
Slow: 146 msec or more	60	94.35	10.17				

Table 4: Mean E3 AEP Latency Differences for High, Average and Low WISC IQ Subjects

Group	Number	Mean	Std Dev	Mean Difference	t	df	Significance
High: IQ 120 or more	81	102.78	19.17				
				17.90	7.23	484	p .00001
Average: 92-119	405	120.68	25.85				
				10.57	3.86	483	p .00001
Low: 91 or less	80	131.25	30.02				

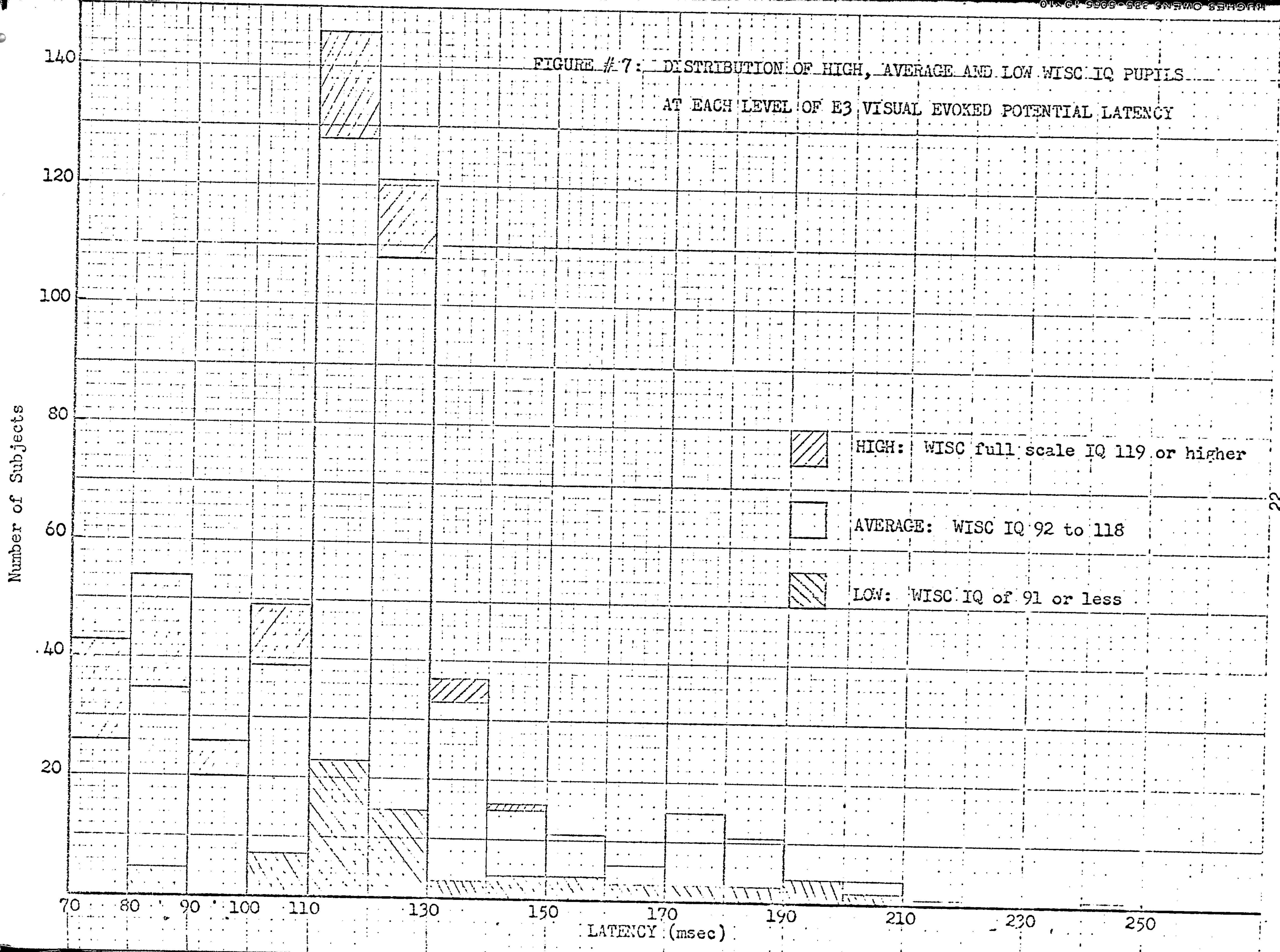
FIGURE # 8: VISUAL AVERAGE EVOKED POTENTIAL WAVEFORMS FOR TEN HIGH and LOW IQ SUBJECTS.



control all potentially interfering variables in this study but it is highly unlikely that the observed relationship between visual AEP component latency and psychometric intelligence could be attributed to any of these uncontrolled variables.

Figure 7 shows the distribution of high, average and low WISC IQ subjects for each value of E3 AEP latency. This figure provides for the identification of "anomalous" subjects, i.e. - subjects whose performance on the IQ test does not accord with their AEP latency as predicted by the inverse relationship between these variables observed across the entire sample. AEP latency was assumed to be a fixed physiological measurement which should predict IQ, a measure known to vary across testing occasions. With this in mind we classified the entire sample into six groups of "anomalous" subjects as follows: a) five subjects whose AEP E3 latency was faster than 100 msec but whose WISC IQ was below 91; b) seventy-eight subjects whose E3 latency was faster than 100 msec but who showed WISC IQ's in the average range (92 -118); c) one subject whose E3 latency was longer than 140 msec but who showed a WISC IQ above 119; d) forty-two subjects whose E3 latency was longer than 140 msec but who showed WISC IQ's in the average range; e) forty-five subjects whose E3 latency was in the average range (100 - 140 msec) but who showed WISC IQ's of 91 or less; and f) forty-six subjects whose E3 latency was in the average range but who showed WISC IQ's of 119 or higher. In all, 217 subjects or 38% of our sample were classified as "anomalous". One hundred and twenty-eight of these were, however, termed "acceptable anomalies", i.e. - subjects whose IQ performance was lower than would be expected on the basis of their AEP latency. Examination of the protocols of these subjects revealed a high percentage of children with obvious English language deficiency which undoubtedly lowered their IQ's on the psychometric tests used. Fifty-seven of these subjects were retested using the Raven Progressive Matrices and the Goodenough Draw-A-Man Test, two estimates of intelligence presumed to be "culture free". Twenty-eight of these children demonstrated higher intellectual capabilities on the language-free retesting and were consequently reclassified as "non-anomalous". Their psychometric estimate of intelligence was now congruent with their AEP latency. The remaining twenty-nine subjects did not show a significant increase in IQ estimate on the language-free retesting. Nineteen of these children, however, were Italian born and were being reared in a deprived socio-economic climate. Discussions with their teachers emphasized the fact that all of these children manifested anti-intellectual attitudes and had little orientation toward abstract problem solving sets and situations. Perhaps the discrepancy between their AEP latency and psychometric intelligence points to a biological intelligence potential which has not as yet found any channel of expressive behaviour. Eighty-nine subjects or fifteen percent of the sample were classified as "non-acceptable anomalies" i.e. subjects whose psychometric IQ was higher than would be expected on the basis of their AEP latency. Only one of these subjects with an E3 latency of 145 msec and a WISC IQ of above 119 could be considered seriously anomalous. We intend to proceed with a longitudinal follow-up of these "non-acceptable anomalies" in search of a possible explanation of their AEP latency - IQ discrepancy.

FIGURE #7: DISTRIBUTION OF HIGH, AVERAGE AND LOW WISC IQ PUPILS AT EACH LEVEL OF E3 VISUAL EVOKED POTENTIAL LATENCY



Conclusions and Recommendations

We are confident that our data has clearly demonstrated for the first time the existence of a relationship between the electrical responses of the human brain and intelligence as measured by standard psychometric tests. The importance of this relationship will be judged by the research it generates, and by acceptance of the concept of neural efficiency. Cross-validation by independent investigators is immediately suggested and is in fact in progress at three different laboratories.

The study has also provided a wealth of normative data on the visual evoked potential and three widely used psychometric tests of intelligence from a random representative sample of primary school pupils. A unique additional accomplishment is the development of a computer program for objectively analysing and measuring evoked potentials (appendix I).

Despite the size of our sample and the statistical significance of our findings we would suggest that these results be considered only as the first step in identifying the electrophysiological correlates of human intelligence. The next obvious steps should be the exploration of evoked potentials from a variety of unique cortical areas in response to auditory and somatic stimuli in relation to psychometric intelligence. It may be possible to develop a composite index of "neural efficiency" based on evoked potential data from a variety of cortical areas and in response to stimuli in three modalities. An exploration of the relative predictive efficiency of evoked potential latency as opposed to psychometric IQ in forecasting academic achievement and other accepted criteria of intelligent behaviour should be undertaken.

In the long run, our present findings and the work which should follow them could have considerable educational significance. Knowledge of the "neural efficiency" of an individual could be useful as an objective, culturally independent biological assessment of mental potential. Such a measurement could be made at any age even intra-uterine. Questions of racial differences in intelligence could be approached and possibly resolved by this method. Standard IQ tests would not be replaced by this method but would be supplemented by it especially in cases of language difficulty, psychological problems or under any conditions where standard IQ tests are invalid. From here on the theoretical development and pragmatic exploitation of our findings are limited only by time, funding and the justified skepticism of a small segment of the scientific community.

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Appendix I

Development of a Digital Data Acquisition and Computer Based Analysis Facility for Electroencephalographic Data.

1.0 Introduction

The analysis potential of currently available laboratory instrumentation for bio-medical research is restricted to a limited number of special purpose functions. They do not lend themselves readily to the exploration of more sophisticated analysis procedures either because of limited storage, restricted logical capability or insufficient speed. It was therefore considered desirable to develop a digital data acquisition and analysis facility which would allow us to take advantage of available large scale digital computers.

The digital data acquisition system was to include an analog to digital converter with two input channels. Recording was to be carried out on digital magnetic tape with conservative performance requirements in order to ensure reliable operation.

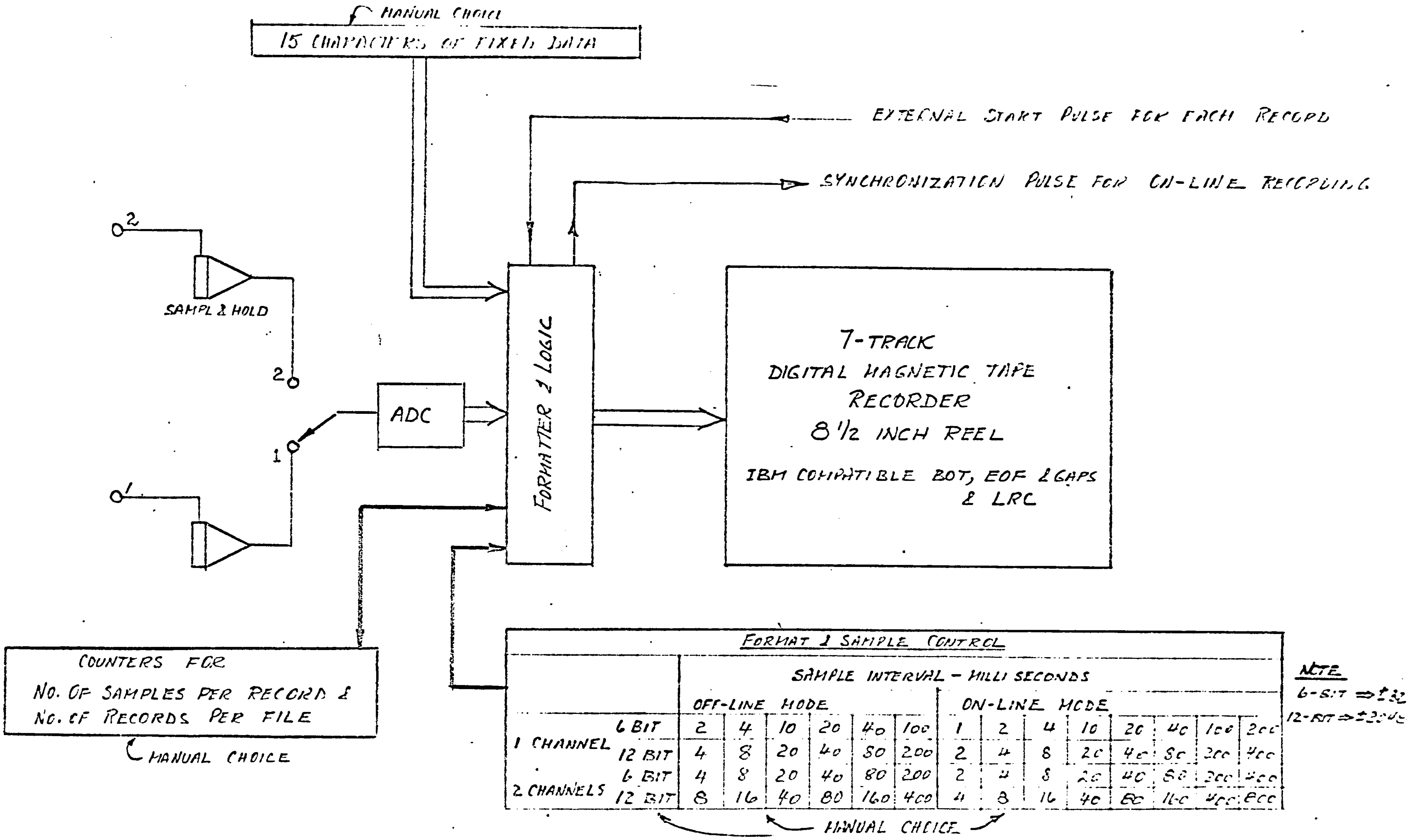
The data analysis facility was to consist of various programs for the formatting of the digital data and for their analysis by means of a variety of statistical procedures. The ultimate aim would be the elimination of all visual interpretations of data by specialised personnel and the optimisation of identification strategies with respect to the research objectives. The PHASE IV C program currently under development is an attempt in this direction (see Appendix II).

It was considered essential to develop this facility in stages so that the investigator would never lose contact with the physical significance of the data and consequently establish confidence in a new tool. For example, it was considered desirable to provide a computer print-out that would resemble familiar graphical representations of data.

The progress report contained herein, attempts to describe in summary form the current status of the facility in section 2.0. In section 3. a summary description of the sequence of events over the past year leading to the present status of the facility is given.

All programs are in an advanced state of detailed documentation. Finalisation is awaiting completion of the final processing of 30 subjects that are now transcribed on digital tape. However, for the convenience of other interested users who are supported by the U.S. Office of Education, these voluminous documents can be made available on request.

The time schedule for the development of the facility has slipped very badly. The initial delays of the equipment delivery were compounded because of replacement of the IBM 360-40 computer



FORMAT & SAMPLE CONTROL

		SAMPLE INTERVAL - MILLI SECONDS													
		OFF-LINE MODE						ON-LINE MODE							
1 CHANNEL	6 BIT	2	4	10	20	40	100	1	2	4	10	20	40	100	200
	12 BIT	4	8	20	40	80	200	2	4	8	20	40	80	200	400
2 CHANNELS	6 BIT	4	8	20	40	80	200	2	4	8	20	40	80	200	400
	12 BIT	8	16	40	80	160	400	4	8	16	40	80	160	400	800

2.0 SUMMARY DESCRIPTION OF DIGITAL DATA AQUISITION SYSTEM. USCE PROJ. No. L-1545 at the University of Ottawa to a model 360-65. The transfer of programming assistants who participated in the earlier stages of the program also contributed to the delay.

As a consequence of the delays, we do not have a sufficient analysis of data by digital methods. However, we are including an example print-out of the PHASE IV A analysis that illustrates the output from this program (see Appendix III).

2.1 Summary Description of the PHASE III Program for the Conversion of Digital Data from 7-Track to 9-Track Tape

This program accepts data recorded on 7-track 200 BPI, odd parity magnetic tape which is generated on the data acquisition s system described in 2.0, and contains one or more files per reel. Each file consists of a header record that is followed by an arbitrary number of data records, each separated by an inter-record gap. The header record contains information on the file length and the format of the data characters.

The PHASE III program accepts also one pair of punched cards for each data channel that is digitised by the data acquisition system. The information contained on these cards is used to verify the tape header and to extend the header with information about the subject name, sex, age and other key data.

On reading and identifying a tape header the PHASE III program will demultiplex the data and add 32 or 2048 to each data point depending on the recording format being in the 6-BIT or the 12-BIT mode respectively. The resulting data are then recorded on 9-track, 800 BPI tape using the I2 or the I4 format. The data are blocked up to 10 records per block and the tape is preceded by a labeled file.

2.2 Summary Description of the PHASE IV A Program

The PHASE IV A program accepts data from a 9-track digital-magnetic-tape-recording generated by the PHASE III program described in section 2.1. The program is equipped to accept data unconditionally from the input tape or to select a specific subject on the basis of:

- Identification Code
- Sex
- Age
- Grade
- Filter Type
- IQ Score

Following the reading of the data, the program will preprocess these by removing the bias and converting to floating point.

The following analysis will then be executed:

For convenience of notation let the Ith data point in the Jth block be $X_J(I)$ where I=1,...,M. J=1,...,N. This subroutine will perform the following calculations on N blocks of data, each containing M data points, which are read from a magnetic disc associated with device code number 12.

1) An amplitude average for back data point in a block over the N data blocks is calculated and stored in array XAV where

$$XAV(J) = \frac{1}{N} \sum_{I=1}^{N} X_I(J) \text{ for } J=1,\ldots,M$$

2) The standard deviation from the mean is stored in array SIG

$$SIG(J) = \sqrt{\frac{1}{N-1} \sum_{I=1}^{N} [X_I(J) - XAV(J)]^2} \text{ for } J=1,\ldots,M$$

3) The upper limit of the confidence interval over two standard deviations will be stored in array ALIM

$$ALIM(J) = 2*SIG(J)/\sqrt{N} \text{ for } J=1,\ldots,M$$

4) The average upper limit of the confidence interval is computed from

$$ALIMAV = \frac{1}{M} \sum_{J=1}^{M} ALIM(J)$$

5) Array EXAMP indicates when, and if so, by how much an average amplitude exceeds the confidence limit. It is computed from

$$EXAMP(J) = 2*XAV(J)/ALIMAV \text{ when } |XAV(J)| > ALIMAV$$

$$= 0 \text{ otherwise for } J=1,\ldots,M$$

6) The mean value of the average of the amplitude is found

$$XAVAV = \frac{1}{M} \sum_{J=1}^{M} XAV(J)$$

7) The RMS-value of the amplitude averages is computed from

$$XAVRMS = \frac{1}{M} \sum_{J=1}^{M} [XAV(J)]^2$$

8) A count of the number of zero crossings is stored in array H(J) J=1,...,M. A zero crossing has occurred at the instance J

if sign ($X_I(J)$) is positive and sign ($X_I(J+1)$) is negative

and if $[X_I(J) + X_I(J+1)] > 0$

else the zero crossing occurred at the instance J+1.

9) The mean count of zero crossings is computed from

$$HAV = \frac{1}{M} \sum_{J=1}^{M} H(J)$$

10) A smoothed zero crossing histogram, using the weights ALP0,ALP1,ALP2,ALP3 as provided by the calling program, is stored in array HS where

HS(J) = 0 J=1,2,3,M-2,M-1,M

HS(J) = [ALP3*(H(J-3) + H(J+3)) +
ALP2*(H(J-2) + H(J+2)) +
ALP1*(H(J-1) + H(J+1)) +
ALP0*H(J)]/2(ALP3+ALP2+ALP1) + ALP0)

11) Array EXZERO indicates when the smoothed zero crossing histogram exceeds the 95% and 99% confidence limit. EXZERO is determined as follows

$$\begin{aligned}
EXZERO(J) &= +\ 95. \quad \text{if } HS(J) - HAV \geq \sqrt{1.92*HAV} \\
&= +\ 990. \quad \text{if } HS(J) - HAV \geq \sqrt{3.31*HAV} \\
&= -\ 95. \quad \text{if } HS(J) - HAV \leq -\sqrt{1.92*HAV} \\
&= -\ 990. \quad \text{if } HS(J) - HAV \leq -\sqrt{3.31*HAV} \\
&= 0 \text{ everywhere else} \\
&\quad \text{for } J=4,5,\ldots,M-3. \\
EXZERO(J) &= 0 \text{ for } J=1,2,3,M-2,M-1,M
\end{aligned}$$

12) A count of the number of peaks is stored in array HP(J), J=1,...,M. A peak has occurred if

Sign $\{X_I(J-1) - X_I(J-2)\}$ is positive and

Sign $\{X_I(J) - X_I(J-1)\}$ is negative,

and will be counted at the instance J-1.

13) The mean count of peaks is computed from

$$HPAV = \frac{1}{M} \sum_{J=1}^{M} HP(J)$$

14) A smoothed peak occurrence histogram, using the weights BET0,BET1,BET2,BET3 as provided by the calling program, is stored in array HPS where

$$HPS(J) = 0 \quad J = 1,2,3,M-2,M-1,M$$

$$\begin{aligned} HPS(J) = [&BET3*(HP(J-3) + HP(J+3)) + \\ &BET2*(HP(J-2) + HP(J+2)) + \\ &BET1*(HP(J-1) + HP(J+1)) + \\ &BET0*\ HP(J)]/(2(BET3 + BET2 + BET1) + BET0) \end{aligned}$$

15) Array EXPK indicates when the smoothed peak occurrence histogram exceeds the 95% and 99% confidence limit and is determined from

$$\begin{aligned} EXPK(J) &= +\ 95. \text{ if } HPS(J) - HPAV \geq \sqrt{1.92*HPAV} \\ &= +\ 990. \text{ if } HPS(J) - HPAV \geq \sqrt{3.31*HPAV} \\ &= -\ 95. \text{ if } HPS(J) - HPAV \leq -\sqrt{1.92*HPAV} \\ &= -\ 990. \text{ if } HPS(J) - HPAV \leq -\sqrt{3.31*HPAV} \\ &= 0 \text{ everywhere else} \\ &\quad \text{for } J=4,5,\ldots,M-3 \\ EXPK(J) &= 0 \text{ for } J=1,2,3,M-2,M-1,M. \end{aligned}$$

16) Elements of the array XAV from XAV(JL) to XAV(JH) are Fourier transformed. The amplitude and phase of this transform from frequency f = FL to f = FH Hz is calculated and stored in arrays AFSQR and PHI respectively. The phase calculation allows for the fact that the specified JL may be greater than 1. An array FRQ is generated, which contains the frequencies at which amplitude and phase have been calculated. The quantities that are generated as described above are communicated to subroutine HEADPR through the labelled common/PRINT/.

3.0 Evolution Chart for the Development of a Digital Data Acquisition System and a Digital Data Processing Facility on Large Computers. U.S.O.E. Project No. 6-1545

Sept. 1, 1968 E.R.F.

DATE Start	Finish	Link	Job Description	Remarks
	Jul. '67		Specifications for Digital Data Acquisition System and Request for Quotation	
	Aug. '67		Issue of Purchase Order	
	Jan. '68		Test tape submitted by Mnfctr.	
Jan.15	Mar.22 '68		System delivered, installed, checked-out and accepted	
Sep.2	Sep.18 '67		Specification of Phase III Program for the conversion of 7-track to 9-track tape	
Sep.18	Sep.26 '67		Implementation of Phase III Progr. by IBM system engineer. on Univ. of Ottawa 360 -MOD. 40.	
Jan.'68	Mar.8 '68		Check-Out of Phase III Program on IBM 360-MOD. 65 at Dep. of Revenue	At this time the universities 360-40 was being replaced by a 360-65. The IBM systm. engineer who developed the Phase III program had been transferred and the computing centre decided against maintaining 7-track input contrary to initial agreement
Jul.'67	Dec.'67		Development of a Pseudo-Random Pulse Generator Compatible with System Specifications.	
Jan.'68	Jul.'68		Aquisition of EEG Data on Analog Tape	
	Apr. '68		Off-Line Translation of Preliminary Test Cases on 7-track tape	
May	Jun. '68	A	Conversion of one reel of 7-track to 9-track tape	At this stage other computer facilities had to be used because 7-track service was no longer available at the U. of Ottawa. This lead to various delays and complications.

DATE Start	Finish	Link	Job Description	Remarks
	Sep. '67		Specification of General Purpose Sub-program for Digital Filtering via Fast Fourier Tranform.	
	Dec. '67		Implementation in Fortran & Check-out on IBM 360-50 at NRC.	
	Nov. '67		Specification of General Purpose Sub-program for Graphically Enhanced Print-Out	
Nov.	Jan.'68		Implementation in Fortran and Check-out on IBM 360-50 at NRC.	
Nov.'67	Jan.5 '68		Specification of Phase IV A Program for the Preliminary Analysis of EEG Data from 9-track tape. This program provides for amplitude averaging, peak and zero-cross counting, statistical exceedance calculation and fourier transform of average evoked response.	
Jan.	Feb. '68	A	Implementation of Phase IV A Program on IBM 360-50 at NRC.	
Feb.	June '68		Check-out of Phase IV A at NRC.	This unusual delay is a consequence of a variety of technical and personnel factors. During this interval the university CCMP. CNTR. also reversed a decision not to provide 7-track tape service. This service is now available.
Jun.	Sep. 15*	B D	Transfer of the operational Phase IV A Program to the University of Ottawa IBM 360-65	
	Aug. '68		Off-line translation of 30 subjects to 7-track digital mag. tape	
	Sep.20*		Conversion from 7 to 9-track tape at University of Ottawa 360-65	
			C	

Date Start	Finish	Link	Job Description	Remarks
			C	
Sep.23*	Sep.24*		Analysis of Program by Phase IV A Program at University of Ottawa	
	Sep.27*		Evaluation of Results from Analysis	
		D		
Jul.10	Aug.30		Specification of Phase IV C Program for the Identification of Significant Latencies by a Two Level Strategy.	
Sep.2	Sep.27*		Implementation on IBM 360-50 at NRC	
Oct.1*	Oct.5*		Analysis of Data and Program Check-Out	
	Oct.8*		Evaluation of Results	
Oct.1*	Nov.**		Transfer of Phase IV C Program to University of Ottawa 360-65	

* estimate, ** guess

APPENDIX II

SPECIFICATIONS FOR THE PHASE IV C PROGRAM FOR THE ANALYSIS OF AVERAGE EVOKED RESPONSES OF THE EEG

Submitted by E.R. Funke

1.0 Introduction

The program described here is an extension of previous computer programming and analysis that was executed. It is the first attempt to formalise the identification of significant peaks of the average evoked response, an operation that was heretofore restricted to visual interpretation by specialists.

The strategy for the identification of significant peaks described here follows an analysis of the raw data similar to that performed by the PHASE IV A program. This analysis is described in the text below but reference to the PHASE IV A program description should be made when necessary.

2.0 Conversion of Data Prior to Analysis

The data are recorded initially in the μ volt region, they are then amplified by an amplification factor, C, which is contained in the header record preceding the data. This amplification brings the data up into the volt region compatible with analog magnetic tape recording requirements, which is approximately 3 volts peak to peak.

On play-back the analog magnetic tape recording may have to be filtered and slightly attenuated. The filtering operation must always include an adequate high pass cut-off in order to eliminate all d.c.-bias from the signal. The attenuation on the other hand is to bring the filtered signal into the ± 1 volt range of the converter (i.e. 2 volt peak to peak) and the attenuation constant, AT, should be contained in the header record.

The converted analog samples are then recorded on 7 - track digital magnetic tape either in the 6-bit or the 12-bit format. The particular choice of format is also specified in the header record and is IF = 1 or IF = 2 respectively. The PHASE III program converts data from 7 to 9 track tape and during this process, formats the data to be Fortran compatible. An off-set, K , is also introduced at this point in order to conserve tape storage requirements.

The particular requirements of this program do not necessitate scaling of amplitude values. However, conversion to REAL format will be convenient to avoid overflow during data analysis.

The analog to digital converter will be set to sample the continuous analog record at the rate of once every 2 milli second. However, for the purpose of this analysis only every third data sample will be required. Therefore the samples used in this analysis are spaced by 6 milliseconds in real time and the program must therefore set $\Delta T = 6.0$.

The following preprocessing will be required: If $IX_i(JJ)$ is the JJ th sample in the ith record of an experiment, then

$$X_i(J) = IX_i\ (3*J - 1) - K$$

for $J = 1, 2, 3 \ldots.. , \ \mathrm{Int}\left\{\frac{M}{3}\right\}$

where M are the number of samples per record
as specified by the data header and
K is the off-set which is
= 32 for format IF = 1 and
= 2048 for format IF = 2

3.0 General Structure of the Phase IV C Program

The Phase IV C program should be structured generally as the Phase IV A program except for the intermediate data storage on disk. All other features of selective tape search and header print-out of the Phase IV A must be preserved. Intermediate data storage will not be required here as the following data analysis demands no more than one access to the data.

4.0 Data Analysis for Phase IV C Program

After preprocessing the data will be available in N blocks of $\mathrm{Int}\left\{\frac{M}{3}\right\}$ words each and will be in REAL format. $X_i(J)$ will be defined as the J^{th} element in the i^{th} record for $J = 1,2, \ldots\ldots \mathrm{Int}\left\{\frac{M}{3}\right\}$ and $i = 1,2,3,\ldots N$. The following computations will be performed:

4.1 The Amplitude Average (Average Evoked Response)

$$XAV(J) = \frac{1}{N} \sum_{i=1}^{N} X_i(J)$$

4.2 The Mean Value of the Amplitude Average

For $DM = \mathrm{Int}\{M/3\}$

compute:

$$XAVAV = \left\{\frac{1}{DM} \sum_{J=1}^{DM} XAV(J)\right\} \cdot \frac{1}{K} \text{ volts}$$

where K = 32 computer units per volt for format IF = 1 and
= 2048 for format IF = 2 as specified in the header record.

This mean value of the amplitude average is included in the analysis mainly for the purpose of a check on adequate high pass filtering prior to conversion as this mean value should be reasonably close to zero.

If this mean value must be interpreted in terms of micro-volts for any reason, then the print-out should be divided by the factor (ATMC) where

AT is the attenuation factor and C is the amplification factor as contained in the header record.

4.3 Zero Crossing Calculations

A zero crossing is defined as the event of a change of sign of the continuous variable $X_i(t)$ in a negative going direction. Because of the time discrete representation of the continuous variable we shall define the zero crossing as follows:

A zero-crossing has occurred

IF SIGN $(X_i(J))$ = positive and SIGN $(X_i(J+1))$ = negative. This crossing is counted at the instance J

$$\text{IF } \left[X_i(J) + X_i(J+1)\right] > 0,$$

otherwise it is counted at the instance J+1.

These tests are performed on all the data $X_i(J)$. All events of zero crossings are counted in the array $C_i(J)$. From this one may calculate the frequency of occurrence histogram:

$$H_i(J) = H_{i-1}(J) + C_i(J)$$
$$\text{for } i = 1,2,3 \ldots\ldots N$$

which is equivalent to

$$H(J) = \sum_{i=1}^{N} C_i(J)$$

The mean count of zero crossings is given by:

$$HAV = \frac{1}{DM} \sum_{J=1}^{DM} H(J)$$

where $DM = \text{Int}\left\{\frac{M}{3}\right\}$ as defined before.

4.4 Exceedance Calculations

To test if the frequency count of zero crossings in the J^{th} time cell exceeds the theoretically expected value the following method is used (see GUILFORD p. 237, formula 11.7).

Assuming that the frequencies of occurrence of zero-crossings, H(J), are uniformely distributed over the range $1 \leq J \leq \text{Int}\{M/3\}$ and assuming that HAV is a reasonable approximation to the expected value of the frequency of occurrence for all J, then the ratio $2.(H(J) - HAV)^2/HAV$ is distributed as a chi-square with one degree of freedom. For example for a 99% confidence interval H(J) must therefore fall in the region

$$HAV - \sqrt{3.31 * HAV} < H(J) < HAV + \sqrt{3.31 * HAV} .$$

For reasons of convenience and as the following strategy for latency identification is based on tests for exceedances of at least two levels, which may in addition be modified to explore the most suitable thresholds of decision, an exceedance array shall be defined as follows:

$$\begin{array}{lll} \text{For} & J = 1,2, \ldots\ldots & \text{Int}\{M/3\} \\ & EXZRO(J) = +95 & \text{if } H(J) - HAV \geq \sqrt{A1 * HAV} \\ & \quad = +990 & \text{if } H(J) - HAV \geq \sqrt{B1 * HAV} \\ & \quad = -95 & \text{if } H(J) - HAV \leq -\sqrt{A1 * HAV} \\ & \quad = -990 & \text{if } H(J) - HAV \leq -\sqrt{B1 * HAV} \\ & \quad = \ 0 & \text{everywhere} \end{array}$$

The resulting array EXZRO will be used in the following strategy for peak identification. Following this, the array H(J) will be reanalysed using a different confidence interval. This implies substitution of A2 and B 2 for A1 and B1 in the exceedance calculations above. The values for A1, A2, B1 and B2 are to be specified by one control card in the beginning of the program.

Typical values are:

A1 = 1.92 and B1 = 3.31 corresponding to the 99 and 95% levels
A2 = 1.7 B2 = 3.00 corresponding to the 97 and 93% levels.

5.0 Strategy for Latency Identification

The following 7 rules describe the strategy of significant latency identification as described by Dr. J. Ertl. It may be noticed that a latency is the time displacement of a certain significant peak of the Average Evoked Response (AER) from the instance of the stimulus. The exceedances referred to in the following rules are the events of statistically significant occurrences of zero crossings with negative slopes.

Rule 1) If the exceedance is +99%, then the event is the latency of the largest maximum preceeding the +99% event but following the last preceeding -95% or -99% event.

2) If the exceedance is -99%, then the event is the latency of the largest maximum following this -99% event but preceding the next +95% or +99% event.

3) If the exceedance of +95% is immediately followed by another +95% exceedance, then it will be treated as a +99% exceedance.

4) If the exceedance of -95% is immediately followed by another -95% exceedance, then it will be treated as a -99% exceedance.

5) If the exceedance of +95% follows an exceedance of -95% then the event is the latency of the largest maximum following the -95% exceedance.

6) Adjacent exceedances of weight 99% are considered to be the same event.

7) The latency must be greater than 15 milliseconds from the origin of the average evoked response.

Fig. 1 and 2 are the flow-charts of the proposed program implementation of this strategy. From this flow-chart the following 3 essential rules emerge:

RULE 1: If the exceedance is +99%, then the event is the latency of the largest value of the AER preceding the +99% exceedance but either following the last preceding negative exceedance of -95 or -99% or the 15 millisecond latency whichever occurs latest.

RULE 2: If the exceedance is +95% and if the exceedance just following this is also +95% or +99%, then the event is identified as per RULE 1.

RULE 3: If the exceedance is +95% and if there has been a preceding negative exceedance of -95 or -99% that occurred after the last positive exceedance or after the 15 milliseconds latency whichever occurs latest, then the event is the latency of the largest value of AER preceding this +95% exceedance but following the last negative exceedance of -95 or -99%.

In order to be more general, the following flow-charts use L1 and L2% rather than 95 and 99%.

SUBROUTINE EVENT 1 (EX, A, L, M, IRL1, IRL2, IRL3, ΔT)

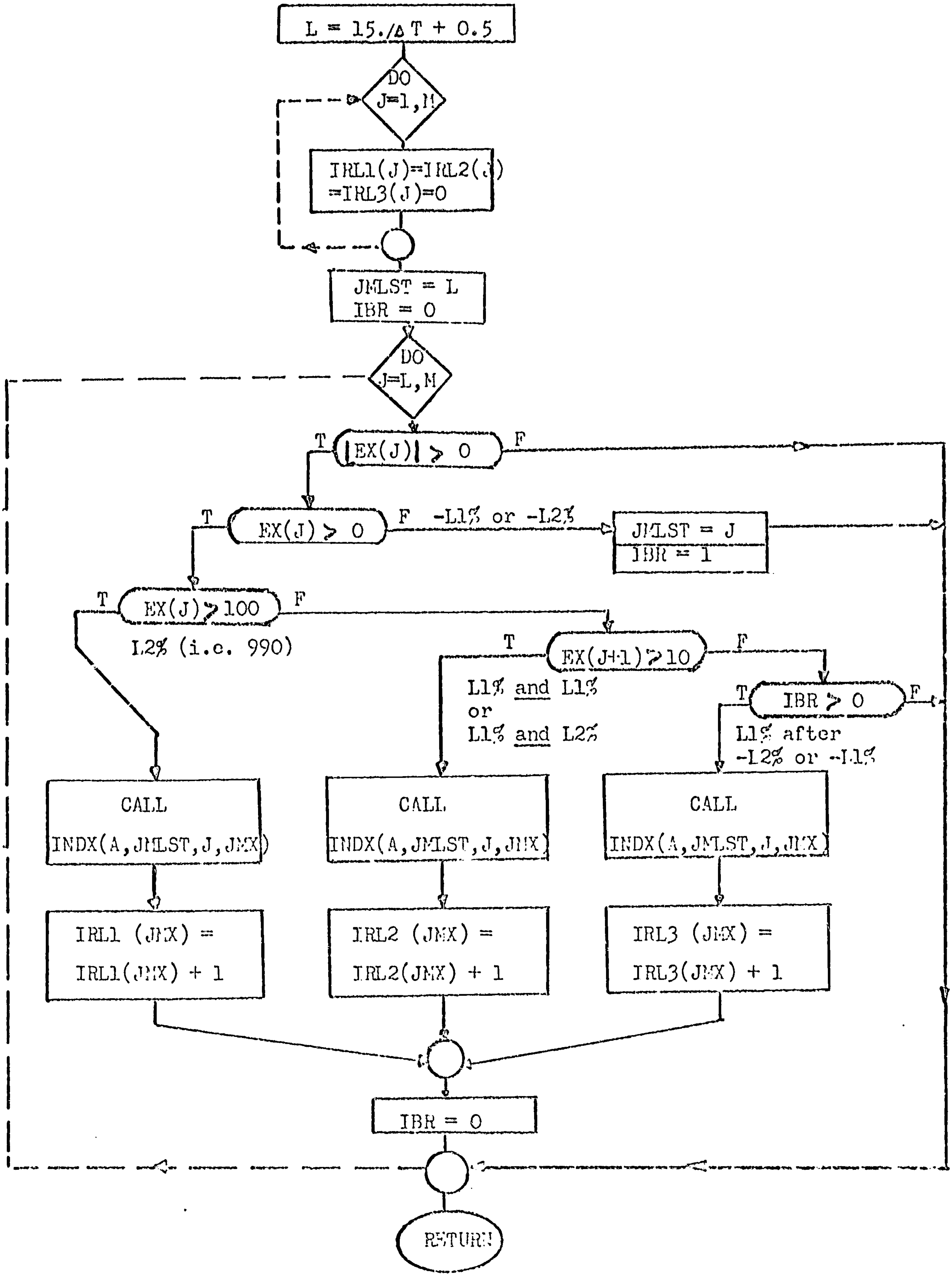


FIG. 1

SUBROUTINE INDX (A, JMLST, J, JMX)

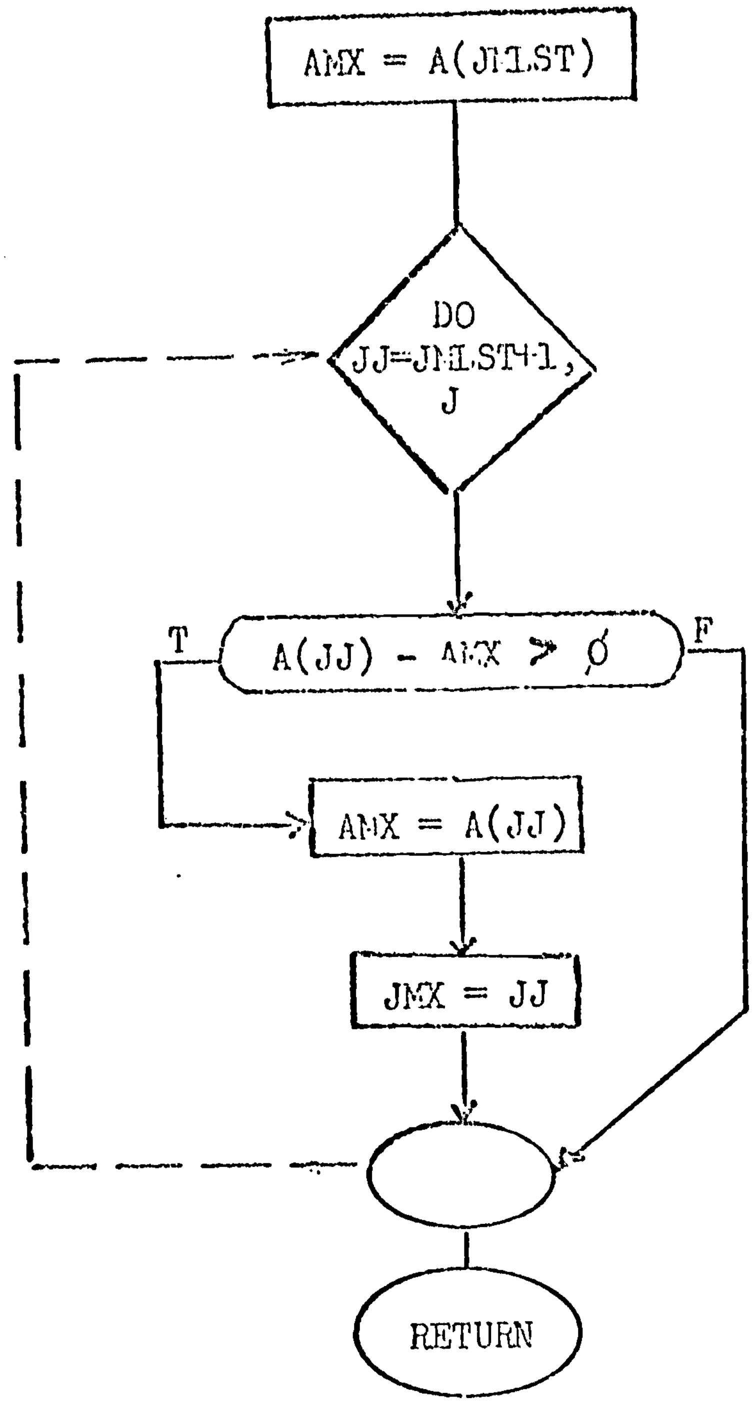


FIG. 2

SUBROUTINE LATNC1 (IRL1, IRL2, L, M, DELT)

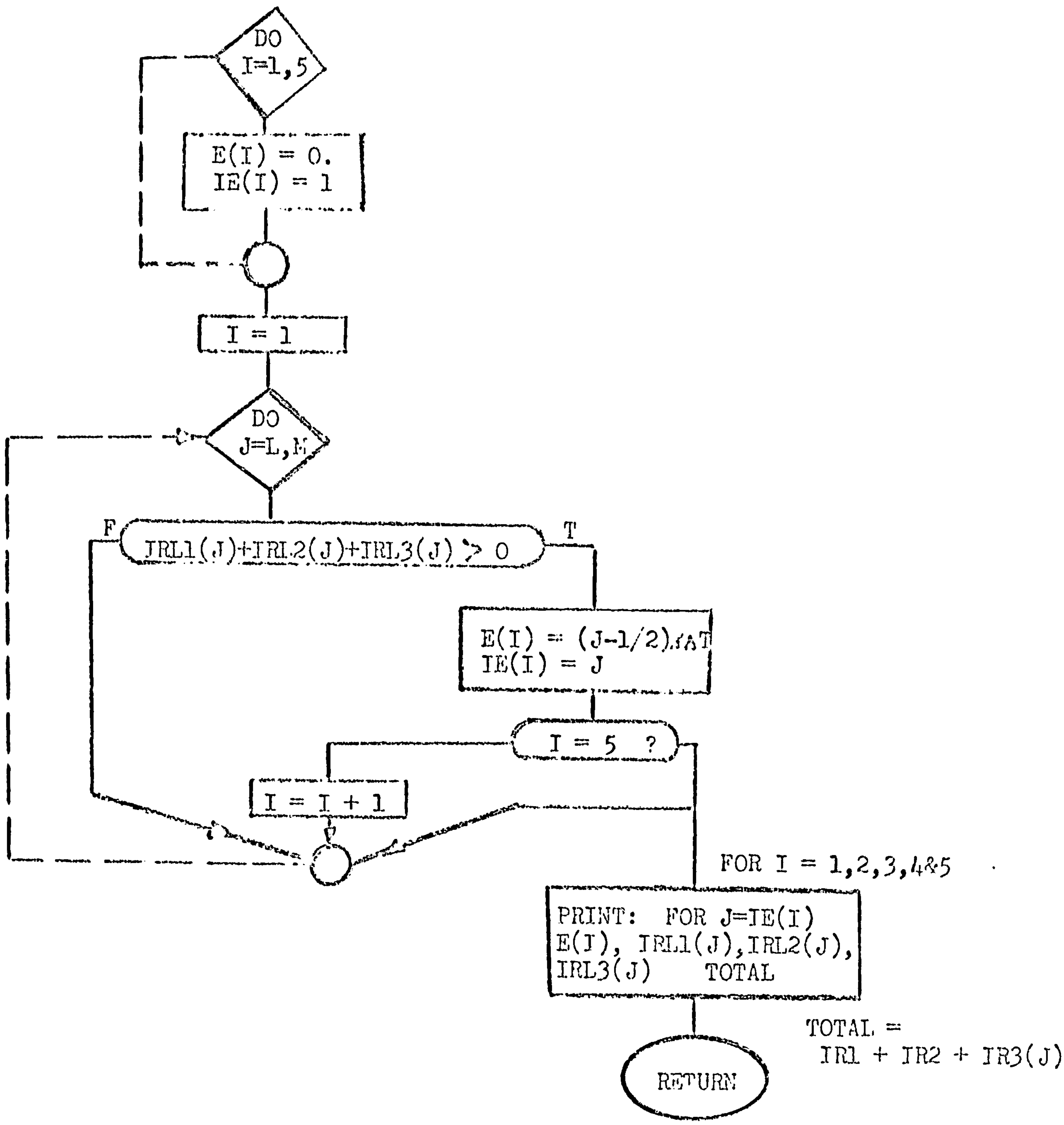


FIG. 3

PRINT-OUT FORMAT, TABLE I

FIRST LEVEL

LATENCY	M. SEC.	RULE 1	RULE 2	RULE 3	TOTAL
E1	32.	1	0	0	1
E2	46.	0	1	0	1
E3	102.	2	0	1	3
E4	160.	1	0	0	1
E5	244.	0	0	1	1
	(F3.0)	(I2)	(I2)	(I2)	(I2)

SECOND LEVEL etc.

6.0 Print-out Requirements

The print-out of results for the PHASE IV C program consists of two sections. The first consists of a header identical to that specified in the PHASE IV A program, with the exception of the last two lines containing information on calculations that are no longer executed here. There are only two variables that should be printed instead. These are the MEAN CNT. OF ZERO CR. and the MEAN OF AV. EV. RESPS. corresponding to HAV as specified by 4.3 and XAVAV as specified by 4.2 above.

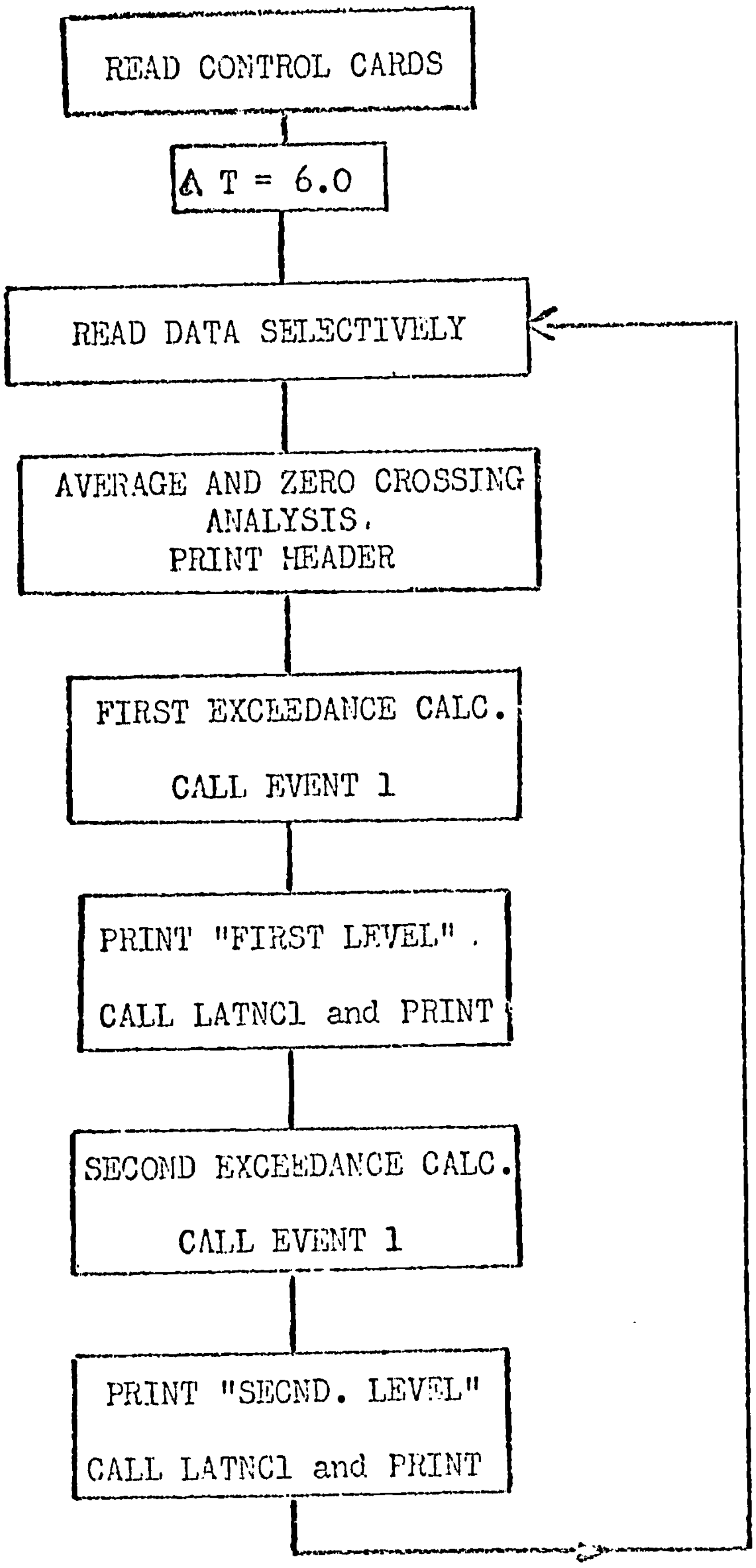
The second print-out consists of the results from the peak-identification strategy. An example is given in TABLE I.

The print-out of the variables is executed by the subprogram LATNC1. This program is flow-charted in Fig. 3 and scans the arrays IRL1 to IRL3 for non-zero values. If a non-zero value is detected, the subprogram computes the "latency" as $E(I) = (J - 1/2). \Delta T$ and also remembers the index J for which a non-zero value in the IRL arrays occurred by substituting $IE(J) = J$.

The print-out, as shown in TABLE I, is therefore as follows: For $I = 1,2, \ldots 5$, $J = IE(I)$ and

"LATENCY"	"M.SEC."	"RULE 1"	"RULE 2"	"RULE 3"	"TOTAL"
"EI"	E(J)	IRL1(J)	IRL2(J)	IRL3(J)	IRL1(J) + IRL2(J) + IRL3(J)

7.0 Summary of Program Sequence



Appendix III

Specimen Computer Readout of Analysed AEP Data

VISUAL EVOKED RESPONSE EEG ANALYSIS, TYPE.A, IDENTIFICATION CODE 2.1

MEAN OF AV. EV. RESPS. = -71452E-01, MEAN CNT. OF ZERO CR. = 0.30714E+02

FIRST LEVEL

LATENCY	M.SEC	RULE 1	RULE 2	RULE 3	TOTAL
E1	33.	1	0	0	1
E2	93.	5	0	0	5
E3	183.	2	0	0	2
E4	0.	0	0	0	0
E5	0.	0	0	0	0